INNSPUB

International Journal of Biosciences | IJB |
ISSN: 2220-6655 (Print); 2222-5234 (Online)
Website: https://www.innspub.net
Email contact: info@innspub.net
Vol. 27, Issue: 3, p. 186-200, 2025

RESEARCH PAPER OPEN ACCESS

Diagnosis of constraints in inland aquaculture in southern Benin

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Key words: Inland aquaculture, Constraints, GIS, Sustainable management, Southern Benin

DOI: https://dx.doi.org/10.12692/ijb/27.3.186-200 Published: September 22, 2025

ABSTRACT

Inland aquaculture contributes to food security, employment, and economic development in Benin. However, its expansion remains limited due to numerous constraints. This study aims to assess the challenges faced by the aquaculture sector in southern Benin. Climatological, geographical, aquaculture, and socioeconomic data were collected from national and international databases, and field surveys were also conducted on aquaculture farms. The results reveal that aquaculture is predominantly practiced by men (88.87%) with a university-level education (24.19%), mainly driven by passion (77.10%), and primarily raising *Oreochromis niloticus* (60.56%) in ponds (72.73%). Nevertheless, the sector faces several constraints such as financial difficulties (57.89%), predator management (34.49%), and poor market access (19.65%). Between 2005 and 2024, strong anthropogenic dynamics led to the regression of swamp forests (−278.4 km²) and mangroves (−68.98 km²), in favor of croplands and fallow lands. The loss of 8.63 km² of water bodies to urban expansion has caused ecological imbalances, including the flooding of aquaculture farms. An integrated approach, combining technical and financial solutions with sustainable management of aquatic ecosystems and surrounding agricultural lands, is essential to address these challenges.

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INTRODUCTION

Inland aquaculture, which primarily involves the farming of fish and other aquatic species, is experiencing growing momentum globally and is increasingly recognized as a valuable agricultural activity. It represents a key sector for economic development and food security in many regions (FAO, 2019; Faiza *et al.,* 2024). In West Africa, aquaculture has emerged as a viable solution to meet the growing demand for animal protein, especially in densely populated countries like Benin (Pèlèbè *et al.*, 2019; Codjo *et al.,* 2023).

Over recent decades, this industry has experienced rapid growth in Benin, supported by the abundance of natural water resources. The country has many rivers, ponds, lakes, and reservoirs, mainly in the southern regions such as Mono, Atlantique, Ouémé, and Zou, which are favorable for aquaculture (Belco Latifou *et al.,* 2020; Hountondji, 2022). Beninese aquaculture is dominated by the farming of fish species such as tilapia and catfish (Gansa *et al.,* 2018; Pèlèbè *et al.,* 2019). Fish farming helps meet the increasing demand for aquatic products, particularly in the south, where water resources are becoming scarcer due to urban expansion and population growth (Gbodja *et al.,* 2022).

Additionally, aquaculture in Benin is an important economic asset, creating jobs in rural areas-particularly for youth and women and thus contributing to poverty reduction in those regions (Kpenavoun *et al.,* 2017). However, despite being the dominant aquaculture subsector in Benin, fish farming remains underdeveloped. Its contribution to the country's total production is modest, accounting for only about 3% (MAEP, 2016). While farmed fish production increased from 309 tons in 2009 to 1,489 tons in 2014 (MAEP, 2016), the trend reversed between 2018 and 2022, falling from 5,114 tons to 2,528 tons. In 2023, aquaculture production reached 2,470 tons, marking a 2.3% decrease compared to 2022 (DSA, 2024). These figures illustrate that, despite the country's favorable natural resources, production challenges persist in Benin. Assessing the constraints facing inland aquaculture in the southern part of the country is therefore essential to understand the root causes of these limitations and identify appropriate solutions.

Inland aquaculture is an increasingly important contributor to food security, livelihoods and rural employment across Africa but remains constrained by technical, environmental and socioeconomic barriers that limit its growth and sustainability (FAO, 2019). Regional syntheses and sector reports highlight the potential of inland aquaculture to supply affordable animal protein while also warning that wetland loss, competition for water and inadequate access to finance, inputs and markets are major constraints to expansion (FAO, 2019). These constraints are particularly acute where aquaculture is concentrated in swampy and lacustrine landscapes that are undergoing rapid land-use change and urban expansion, driving habitat loss, flooding risk and increased predator–farm interactions (Convention on wetland, 2022). In Benin specifically, production statistics and local case studies show variable growth and important local bottlenecks (production rebounds followed by declines), indicating that national potential is not being realised because site-level, social and landscape drivers have not been comprehensively diagnosed and integrated into development actions (DSA, 2024). Together, these observations justify a targeted, spatially-explicit assessment of the constraints that hinder inland aquaculture development in southern Benin.

Research on aquaculture in Benin and sub-Saharan Africa has addressed farm typologies (Adegbola *et al.,* 2022), traditional floodplain systems (Dagoudo *et al.,* 2024), cage and pen culture (Pèlèbè *et al.,* 2019), feeding strategies (Aïzonou *et al.,* 2023), and local feed resources Adéyèmi *et al.,* 2020), while continental reviews highlight recurring constraints like feed, seed, finance, and expertise (Obiero *et al.,* 2019). However, no study has yet linked farm-level constraints with broader landscape dynamics such as wetland change, urban growth, or flooding. This study fills that gap by integrating technical, socioeconomic and environmental constraints with spatial land-use analysis to guide targeted interventions.

This study therefore aims to (1) identify and quantify the primary socioeconomic, technical and environmental constraints affecting inland aquaculture operations in southern Benin, (2) map the spatial distribution of those constraints (for example, flood-prone sites, predator-affected farms and water supply problem areas), and (3) relate local farm constraints to recent land-use and wetland dynamics in the region so that integrated, evidence-based management and policy recommendations can be developed. These aims will be achieved through a combination of farm surveys, field verification and multi-date land-use/remote sensing analysis.

MATERIALS AND METHODS

Study area

Southern Benin, located in West Africa between 1°33'37" and 2°47'36" East longitude and 6°09'20" and 7°46'31" North latitude (Fig. 1; INSAE, 2016), spans 17,440.26 km². It has a humid sub-equatorial climate with a long rainy season (April-October, >1,000 mm/year, 25-32°C) and a dry season (November-March, <50 mm/month, <60% humidity) (INSAE, 2016). The diverse vegetation includes tropical forests, wooded savannas, and coastal mangroves with species like iroko and oil palm (Balagueman *et al.,* 2017; Gansa *et al.,* 2023).

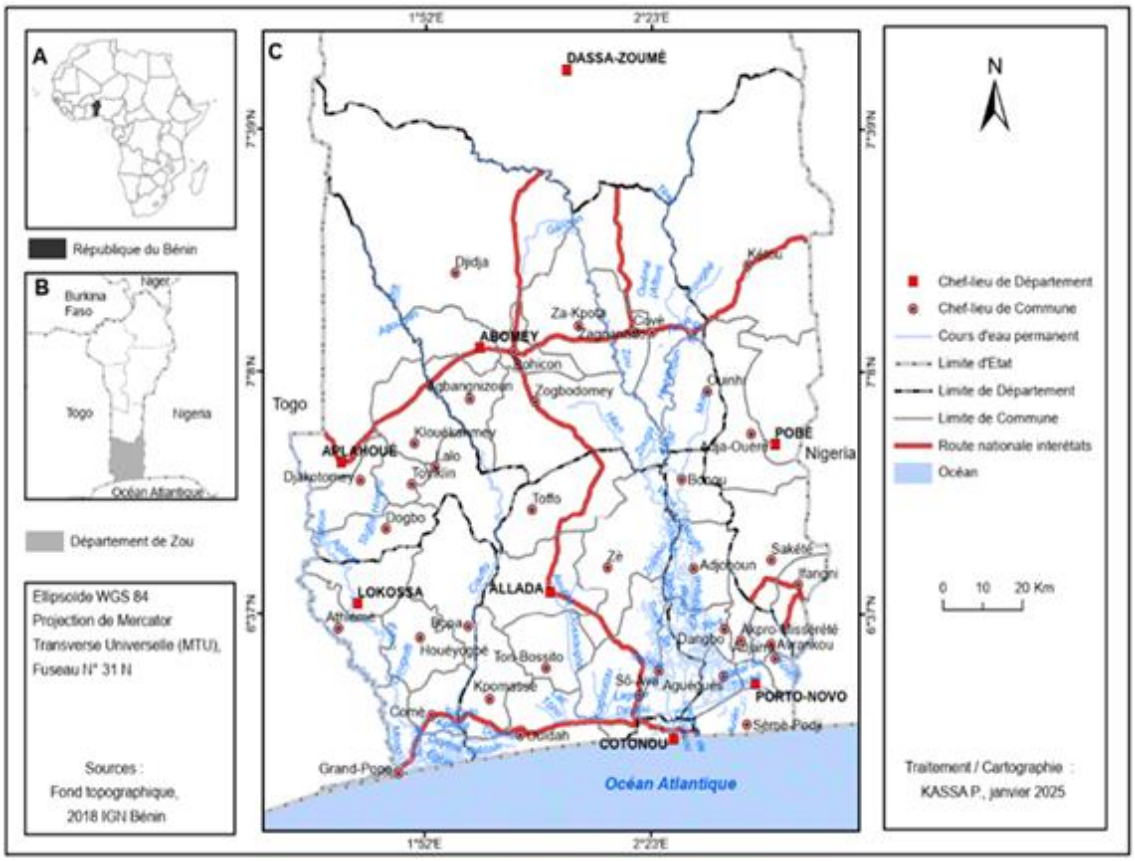

Fig. 1. Map of the study area (Southern Benin)

The region is mostly flat, becoming undulating eastward (FAO, 2022), and is rich in rivers (Ouémé, Sô) and water bodies (Lake Nokoué, Lake Ahémé), crucial for aquaculture (Djihouessi and Aina, 2018; Baglo *et al.,* 2024). This area hosts Agricultural Development Hub No. 7, encompassing nearly 6,000 fish farmers (Promac, 2021) and concentrating the majority of Benin's fish farmers, primarily raising catfish and tilapia. The distribution of ethnic groups, like the coastal Tofin, Xwla, and Sahouè, and inland Fon, Adja, and Aïzo, influences aquaculture, with Goun and Yoruba communities also engaging in it near lacustrine zones (INSAE, 2017). Densely populated cities like Cotonou and Porto-Novo provide large markets for aquaculture products (DSA, 2019).

Data collection

This study utilized diverse data, encompassing climatological, geographical, aquaculture, and socioeconomic domains. Climatological variables, such as temperature, precipitation, and relative humidity, were sourced from the CRU database (1951–1990) and ASECNA (2020 to 2024). Geographical data, including hydrography and topography (from the Directorate General of Water and the CRU Digital Elevation Model), alongside locality information from the Directorate of Fisheries, helped define the study area. Biotic data were derived from the 2012 INSAE national census and SPOT Vegetation imagery (2021–2023). For aquaculture-specific variables, direct site visits and surveys were conducted with fish farmers identified via the Directorate of Fisheries Production. A survey form, designed with the KoboCollect mobile application, facilitated efficient and high-quality data collection and initial analysis, eliminating double entry and enhancing surveyor mobility (Mbourou, 2023).

Data analysis

Data analysis for this study employed a comprehensive suite of software tools encompassing Geographic Information Systems (GIS), spatial analysis, remote sensing, data analysis/modeling, and GPS management. ArcView 3.2 (with Spatial Analyst) and ArcGIS 10.8 (with Spatial Analyst and Geostatistical Analyst extensions), both by ESRI, were crucial for GIS and spatial analysis tasks like geometric transformations, projections, interpolations, and hypothesis testing through indicators such as standard deviation ellipses and spatial autocorrelation indices. These tools also facilitated the modeling and mapping of aquaculture site distributions based on environmental factors. For remote sensing, ERDAS Imagine and ENVI were primarily used to process NDVI images, handling georeferencing, cropping, and calculating average NDVI values. Statistical data processing and modeling were performed using SPSS 18.0, SAS, and MINITAB for analyses like Principal Component Analysis and regression model selection. GPS mapping software, including UTM GeoMap, GPS TrackMaker, Odilon Ferreira Junior, and DNR Garmin, enabled the download of aquaculture site coordinates. ENVI was also key for land use classification and mapping, involving legend definition, class setting, training zone creation, spectral signature analysis, classifier selection, and result validation. Land use change analysis was conducted using multi-date and macro-scale satellite observations from Landsat TM images (2015 and 2023), processed via geometric correction and resampling with ILWIS 3.2, contrast enhancement, visual identification of spectral classes, on-screen digitization, and ground-truthed interpretation sketches (with a valid Kappa Index between 50% and 75%). Cartographic presentation and observation were executed using ArcGIS 10.8, which was also used to calculate the surface area of land use cells via its ArcToolbox component. Land use dynamics were analyzed by calculating the average annual rate of spatial expansion, applying a formula (Bernier, 1992) to measure the growth of spatial units between two time periods, using surface area (S) for 2015 (S_1) and 2023 (S_2). The average annual rate of spatial expansion (T) was calculated using the following formula:

$$T = \frac{(\ln S2 - \ln S1)}{t \ln e} \times 100$$

Where: t is the number of years of evolution; ln is the natural logarithm and e is the base of natural logarithms (e = 2.71828).

RESULTS

Socioeconomic and demographic characteristics of fish farmers in southern Benin distribution of aquaculture site promoters by gender

Out of the 748 promoters surveyed, 614 promoters, i.e. 88.87%, were male; 10.13% were female, while 1% were mixed-gender couples. The differences observed between the frequency of men and women on the one hand, and mixed couples on the other hand, are highly significant according to the Chi-square test results for goodness-of-fit to a random distribution ($p < 0.0001$) at a 0.05 significance level. Therefore, in southern Benin, most fish farmers are men.

Distribution of aquaculture site promoters by level of education

A significant proportion of promoters have a relatively low level of education (literate, illiterate, primary), but there is also a notable presence of promoters with secondary or university education. The university level is the most represented category, with 24.19% of the promoters. Primary and secondary levels account for a large share of promoters (17.58% for primary, 14.19% and 13.06% for lower and upper secondary respectively). Overall, there are more illiterate promoters (17.10%) than literate ones (13.87%).

Reasons for the creation of aquaculture sites in southern Benin

Out of the 748 promoters who participated in the survey, only 620 responded to the question about the underlying reason for creating their farms. Among these 620 respondents, 478 promoters (77.10%) stated that they created their production units out of a passion for aquaculture. Unemployment drove 106 promoters (17.10%) to establish aquaculture farms, while 21 promoters (3.39%) inherited their farms from their parents. The differences observed between the frequency of passionate aquaculturists, unemployed individuals, and those who inherited farms are highly significant, according to the Chi-square goodness-of-fit test results ($p < 0.0001$) at the 0.05 significance level. Thus, in Southern Benin, most aquaculture promoters are driven by a genuine passion for aquaculture.

Typology of activities carried out on aquaculture sites in southern Benin

Among the 748 promoters surveyed, 669 responded to the question regarding the types of activities conducted on their aquaculture farms. A total of 361 promoters (53.96%) said they practice aquaculture exclusively. 16.14% combine aquaculture with market gardening, while 29.90% combine aquaculture with other activities (such as livestock farming, processing, etc.).

Typology of species raised on aquaculture sites in southern Benin

Among the surveyed aquaculture sites, *Oreochromis niloticus* (Nile tilapia) is the most commonly raised species, found on 453 sites (60.56%). *Clarias gariepinus* (African catfish) is also widely cultivated, present on 341 sites (45.59%). A smaller number of sites, 31 (4.14%), raise other species such as *Spirulina sp.*, *Parachanna obscura*, *Heterotis niloticus*, *Clarias ebriensis*, *Heterobranchus longifilis*, and *Oreochromis mossambicus*. Additionally, freshwater shrimp are cultivated on just 2 farms (0.27%).

Typology of aquaculture infrastructure in southern Benin

Out of the 748 aquaculture farms surveyed, the majority, 544 farms (72.73%), utilize ponds. Following this, 168 farms (22.46%) employ tanks, with 65 farms (8.69%) specifically using above-ground tanks. Additionally, 39 farms (5.21%) have floating cages, while other operations use various infrastructures such as fixed cages, happas, or artificial lakes.

Temporal dynamics of aquaculture site creation in southern Benin

Out of the 748 promoters surveyed, 463 (61.89%) were able to recall the date their production unit was created. These dates were grouped by year to analyze the temporal dynamics of aquaculture development. Results show that aquaculture has been practiced in southern Benin since the 1960s, following Benin's independence. However, a significant increase in activity has been observed since 2008.

Assessment of constraints related to aquaculture activities in southern Benin

Among the eleven major constraints identified for aquaculture, the most significant are financial difficulties (57.89%), followed by challenges with predator management (34.49%), and low market demand (19.65%). Other notable issues include flooding (13.64%) and problems with water supply (10.43%). Additionally, aquaculturists face hurdles such as the availability of quality feed and fry, labor shortages, land tenure complexities, and the effective management of aquaculture waste (Table 1).

Table 1. Constraints related to aquaculture in southern Benin

Constraint	Count	Percentage (%)
Financial problems	433	57.89
Predator management	258	34.49
Low sales	147	19.65
Flooding	102	13.64
Other issues	83	11.10
Water supply	78	10.43
Feed not available	58	7.75
Fry not available	20	2.67
Labor unavailable	20	2.67
Land issues	7	0.94
Waste management	6	0.80

Spatial distribution of aquaculture farms in southern Benin

Aquaculture sites are highly concentrated in the southeastern and southwestern departments (Fig. 2). It can be concluded that aquaculture farms in Southern Benin are mainly found in marshy areas and close to water bodies.

Spatial distribution of farms facing predator management issues

The aquaculture farms visited face problems related to predator management (Fig. 3). Fish farms located in the southeastern and southwestern departments of Benin face flooding issues (Fig. 4). Water supply difficulties are recurring on fish farms visited in the departments of Ouémé, Mono, and Zou (Fig. 5).

Spatio-temporal dynamics of land use in southern Benin from 2005 to 2024

The land use units identified in 2005 include gallery forests and riparian formations, dense forests, open forests and wooded savannahs, tree and shrub savannahs, swamp formations, mangroves, croplands and fallows, croplands and fallows under oil palm, plantations, eroded and bare soils, rocky or lateritic surfaces, sandy areas or beaches, water bodies, and settlements (Fig. 6). Open forests and wooded savannahs are observed in the northern part of the study area, in the departments of Zou and Plateaux. Croplands and fallows, and croplands and fallows under oil palm are seen in the southern part, notably in the departments of Atlantique, Couffo, and Ouémé. The land use units identified in 2015 include the same categories as in 2005 (Fig. 7).

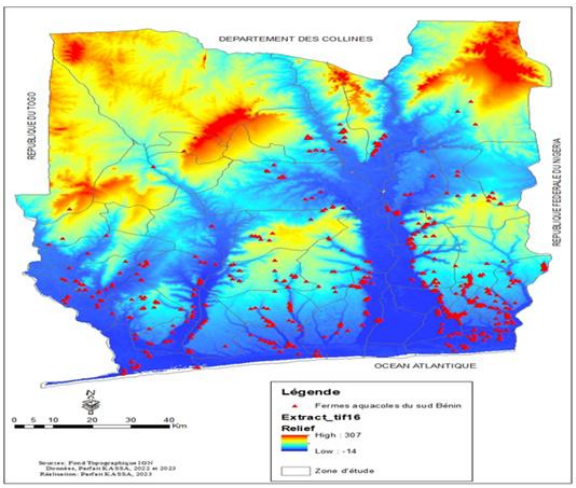

Fig. 2. Spatial distribution of aquaculture farms in southern Benin

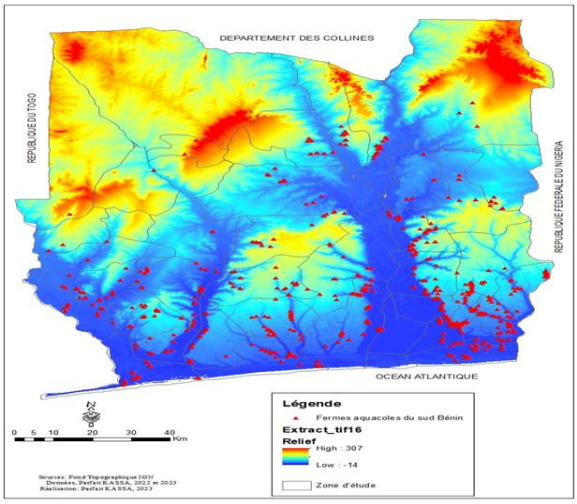

Fig. 3. Spatial distribution of farms facing predator management issues

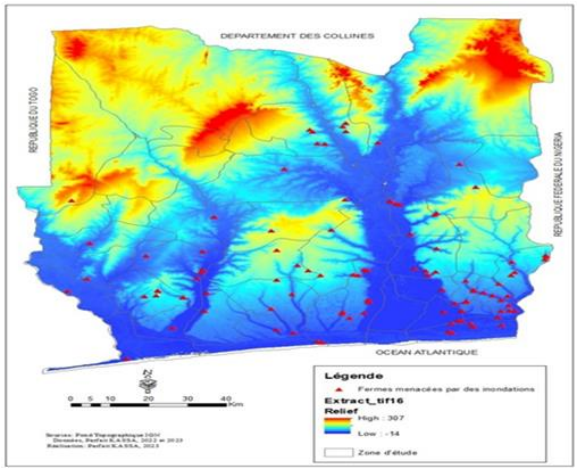

Fig. 4. Spatial distribution of farms affected by flooding problems

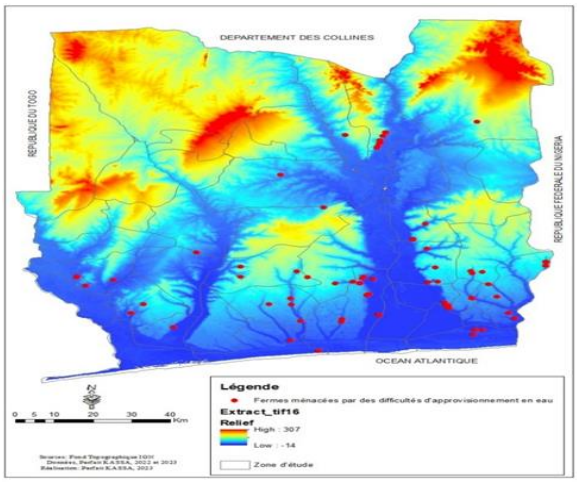

Fig. 5. Spatial distribution of farms with water supply difficulties

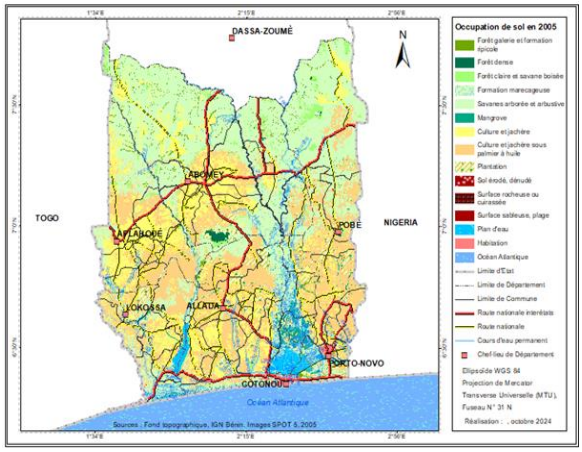

Fig. 6. Land cover in 2005

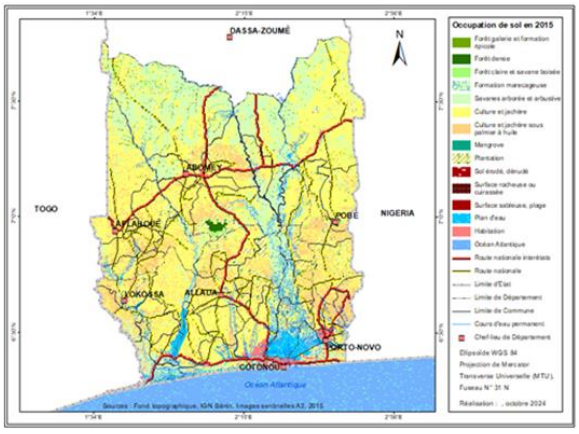

Fig. 7. Land cover in 2015

In 2015, patches of open forests and wooded savannahs are observed in the northern area, along with a narrow strip of gallery forest lining the rivers and tributaries. Croplands and fallows have become increasingly extensive (Fig. 7).

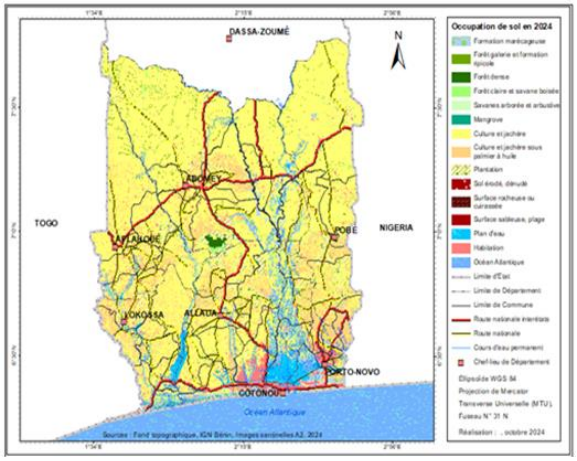

Fig. 8. Land cover in 2024

In 2024, the same land use categories were identified (Fig. 8). Patches of open forests and wooded savannahs are now mainly found in protected areas like the Lama Forest. Croplands and fallows have become the most dominant formations in the study area.

Observed changes in land use units between 2005 and 2024

The transition matrix highlights the various forms of land cover conversion that occurred between two time points. The areas of different land use classes were calculated by overlaying the land +cover maps from 2005, 2015, and 2024. Each cell indicates the area (in km²) that was transferred from one land use class in 2005 to another in 2015 and 2024.

The diagonal shows areas that retained their original land use type, while other values represent changes between classes. Below is an analysis of the main trends (Tables 2 and 3).

From a structural perspective, each column represents a land use class in 2015 and each row its counterpart in 2005. Row totals (2005 area) show the initial area of each class in 2005, while column totals (2015 area) show the total area of each class in 2015. The analysis of land use dynamics between 2005 and 2015 reveals two types of classes: stable and unstable. Among the stable classes, SASa (tree and shrub savannahs) occupy 6605.06 km², followed by CJP (cropland and fallow under oil palm) with 5269.31

km²; CJ (cropland and fallow) with 3406.10 km²; FM (swamp formation) with 730.44 km²; FCSB (open forest and wooded savannah) with 533.89 km²; PE (bare/eroded soil) with 345.84 km²; FGFR (gallery forest and riparian formation) with 296.90 km²; PLT (plantations) with 281.93 km²; Ha (settlements) with 189.27 km²; Mgr (mangroves) with 116.18 km²; FD (dense forest) with 59.20 km²; SR (rocky/lateritic surfaces) with 7.93 km²; SED (sandy areas/beaches) with 7.41 km², and SSP (water bodies) with 3.87 km².

In southern Benin, aquaculture is largely concentrated in swampy areas and near water bodies. Disruption to these wetland ecosystems can significantly harm inland aquaculture. This is precisely what is observed.

Table 2. Land Use Transition Matrix (LUTM) Between 2005 and 2015

OS 2005	OS 2015														Sup 2005 km²
	FGFR	FD	FCSB	SASa	FM	Mgr	CJ	CJP	PLT	SED	SR	SSP	PE	Ha	
FGFR	296.90	0.00	0.00	0.00	0.00	0.00	12.22	6.39	6.21	0.00	0.00	0.00	7.77	6.40	335.90
FD	0.00	59.20	2.05	2.00	0.00	0.00	8.57	3.17	8.17	0.00	0.00	0.00	0.00	0.67	83.84
FCSB	0.00	0.00	533.89	20.01	0.00	0.00	52.63	8.11	7.93	0.00	0.00	0.00	0.00	2.51	625.07
SASa	0.00	0.00	1.26	6605.06	0.00	0.00	880.48	32.85	175.70	0.00	0.00	0.00	0.00	41.00	7736.34
FM	0.00	0.00	0.00	0.00	730.44	0.00	188.39	2.22	5.15	0.00	0.00	0.00	50.50	32.14	1008.83
Mgr	0.00	0.00	0.00	0.00	0.00	116.18	14.54	1.98	4.25	0.00	0.00	0.00	33.15	15.06	185.15
CJ	0.00	0.00	0.00	0.00	0.00	0.00	3406.10	50.11	150.59	13.10	9.00	0.00	1.20	181.33	3811.43
CJP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5269.31	113.70	0.00	0.00	0.00	0.00	109.79	5492.80
PLT	0.00	0.00	0.00	0.00	0.00	0.00	17.00	15.00	281.93	0.00	0.00	0.00	0.00	9.63	323.57
SED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.41	0.00	0.00	0.00	2.00	9.41
SR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.93	0.00	0.00	3.00	10.93
SSP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.87	2.00	1.25	7.12
PE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	345.84	8.63	354.47
Ha	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	189.27	189.27
Sup 2015 km²	296.90	59.20	537.21	6627.07	730.44	116.18	4579.93	5389.14	753.62	20.51	16.93	3.87	440.47	602.68	20174.15

Table 3. Land Cover Transition Matrix Between 2015 and 2024

UOS 2015	UOS 2024														Sup 2015 (km²)
	FGFR	FD	FCSB	SASa	FM	Mgr	CJ	CJP	PLT	SED	SR	SSP	PE	Ha	
FGFR	233.95	0.00	0.00	0.00	0.00	0.00	24.10	8.50	10.61	0.00	0.00	0.00	11.42	8.31	296.90
FD	0.00	11.11	5.42	8.26	0.00	0.00	13.20	7.28	11.43	0.00	0.00	0.00	0.00	2.51	59.20
FCSB	0.00	0.00	375.95	21.27	0.00	0.00	95.98	23.84	14.76	0.00	0.00	0.00	0.00	5.41	537.21
SASa	0.00	0.00	23.12	4594.91	0.00	0.00	1619.84	88.98	223.58	0.00	0.00	0.00	0.00	76.64	6627.07
FM	2.00	0.00	0.00	0.00	375.20	0.00	213.51	21.72	7.25	0.00	0.00	0.00	66.55	44.22	730.44
Mgr	0.00	0.00	0.00	0.00	0.00	40.89	17.80	3.81	3.25	0.00	0.00	0.00	34.15	16.28	116.18
CJ	0.00	0.00	0.00	0.00	0.00	0.00	3353.47	633.99	223.45	33.99	17.00	0.00	4.12	313.90	4579.93
CJP	0.00	0.00	0.00	0.00	9.00	0.00	167.88	4840.90	183.06	0.00	0.00	0.00	0.00	188.30	5389.14
PLT	0.00	0.00	0.00	0.00	0.00	0.00	22.52	19.05	691.84	0.00	0.00	4.00	0.00	16.22	753.62
SED	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	0	7.98	6.97	0.00	0.00	5.55	20.51
SR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.47	0.00	0.00	6.47	16.93
SSP	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.30	0.00	1.57	3.87
PE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	434.26	6.21	440.47
Ha	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	602.68	602.68
Sup 2024 (km²)	235.95	11.11	404.50	4624.44	384.20	40.89	5528.30	5648.07	1369.22	41.98	34.44	6.30	550.50	1294.26	20174.15

From 2005 to 2015, wetland formations experienced significant instability, particularly swamp formations (FM), which lost a total of 278.4 km², predominantly to human-driven activities. Specifically, 188.39 km² of FM converted to cropland and fallow (CJ), 50.50 km² to bare soil (PE), 32.14 km² to settlements (Ha), 5.15 km² to plantations (PLT), and 2.22 km² to cropland and fallow under oil palm (CJP).

This extensive human-induced land conversion directly impacts inland aquaculture and the habitats of predators that affect aquaculture farms. Similarly, mangroves also suffered considerable losses, with 33.15 km² converting to water bodies, 15.06 km² to settlements, 14.54 km² to croplands and fallows, 4.25 km² to plantations, and 1.98 km² to croplands under oil palm.

These results show that mangroves, though legally protected, are being increasingly converted by human activities in southern Benin. Water bodies themselves lost 8.63 km² to settlements. In other words, people are building homes in wetland areas, which explains the flooding of aquaculture farms in this region. Flooding has thus become a major constraint to the development of aquaculture in southern Benin. From the perspective of general structure, each column represents a land use class in 2024, and each row represents the corresponding class in 2015. The row totals (area 2015) indicate the initial area of each class in 2015, while the column totals (area 2024) show the total area of each class in 2024. The analysis of land use dynamics between 2015 and 2024 involves two types of classes: stable classes and unstable classes.

Among the stable classes, CJP occupies 4840.90 km², followed by SASa with 4594.91 km²; CJ (3353.47 km²); PLT (691.84 km²); Ha (602.68 km²); PE (434.26 km²); FCSB (375.95 km²); FM (375.20 km²); FGFR (233.95 km²); Mgr (40.89 km²); FD (11.11 km²); SR (10.47 km²); SED (7.98 km²); and SSP (2.30 km²). From 2015 to 2024, wet vegetation formations experienced instability, similar to the 2005–2015 decade.

For example, FM lost 213.51 km² to CJ, 66.55 km² to PE, 44.22 km² to Ha, 7.25 km² to PLT, 21.72 km² to CJP. In just nine years, this formation lost 353.25 km² to anthropogenic formations, 1.27 times more than during the 2005–2015 decade (278.4 km²). Mangroves also regressed by 75.29 km² during the 2015–2025 decade. This regression is greater than that of the 2005–2015 decade, which was 68.98 km² (Table 3).

Landscape transformations between 2005 to 2024

The main dynamic observed is a conversion of natural areas (forests and savannahs) into agricultural land (CJ and CJP), reflecting an intensification of agricultural activities and the potential to effectively alter the range of predatory fauna around aquaculture farms in southern Benin. Natural formations include forests, tree and shrub savannahs, and marshlands. Agricultural and anthropogenic zones include crops and fallows (CJ), crops and fallows under oil palm (CJP), plantations (PLT), and housing areas (Ha). Other land cover categories include eroded/bare soils (SED), rocky surfaces (SR), water bodies (PE) preferred aquaculture sites and sandy surfaces and beaches (SSP). From 2005 to 2015, natural formations in the area saw a notable decline, with gallery forests and riparian formations (FGFR) decreasing by 0.19% (from 1.67% to 1.47%), dense forests (FD) significantly shrinking by 0.12% (from 0.42% to 0.29%), open forests and wooded savannas (FCSB) falling by 0.44%, and mangroves (Mgr) dropping by 0.34%. Even tree and shrub savannas (SASa), which were the largest land cover type in 2005 at 38.35%, experienced a substantial 5.50% reduction, and marsh formations (FM) saw a significant decline of 1.38%. Conversely, agricultural and anthropogenic zones expanded, with crops and fallows (CJ) growing considerably by 3.81% (from 18.89% to 22.70%). While crops and fallows under oil palm (CJP) slightly decreased by 0.51%, they still made up a large portion of the land (26.71% in 2015). Plantations (PLT) saw marked growth of 2.13%, and housing (Ha) increased significantly by 2.05%, indicating expanding urban and inhabited areas. Among other land cover categories, eroded/bare soils (SED) increased slightly by 0.06%, rocky surfaces (SR) rose by 0.03%, water bodies (PE) grew by 0.43%, and sandy surfaces and beaches (SSP) experienced a slight decline of 0.02%.

Synthesis of balance sheets

From 2005 to 2015, over a period of only 10 years, the total losses of natural areas (forests, savannas, swamps) amounted to -7.97%. During the same period, an increase in agricultural and anthropogenic areas (crops, plantations, dwellings) was noted, reaching +8.49%. The overall balance reflects a massive conversion of natural ecosystems towards anthropogenic uses, marking a significant transformation of the landscape (Fig. 9). Changes between land cover categories occurred differentially across the study area. Within each land cover category, losses, stabilities, and gains were observed, each occupying differential proportions.

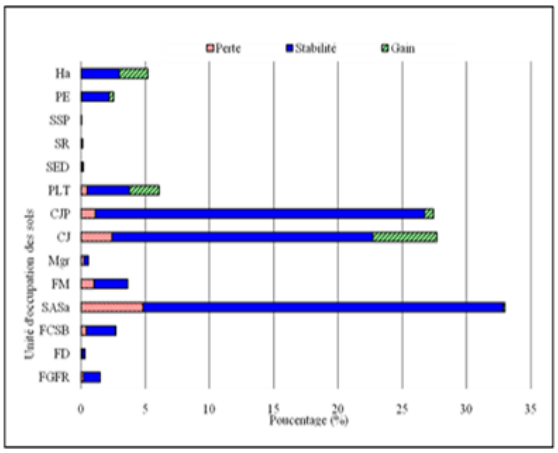

Fig. 9. Land cover change in losses, gains, stability (2005-2015)

Thus, tree and shrub savannas were the land cover categories where changes were most significant, affecting about 38% of the study area, with 5% experiencing losses, 0% gains, and 28% stability.

They are followed by crops and fallows, covering 27% of the study area, with 2% experiencing losses, 5% gains, and 20% stability. Next are crops and fallows under oil palm, covering 28% of the study area. These experienced respectively 1% loss and gain, and 26% stability. Mosaics of fields and fallows underwent minimal changes, with 3% losses against 25% gains and 53% stability in the study area. Dense dry forests, forests and wooded savannas, plantations, and dwellings are the land cover units that experienced very little change (Fig. 10).

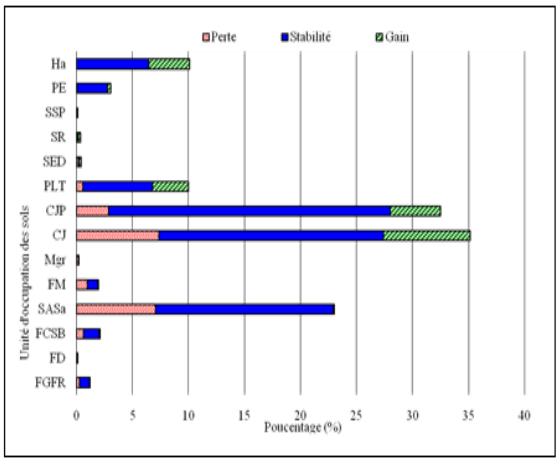

Fig. 10. Land cover change in losses, gains, stability (2015-2020)

Land cover categories experienced gains and losses relative to the study area's total surface. The vertical blue line at 11.15% represents the limit where changes would remain uniform if disturbances ceased in the study area.

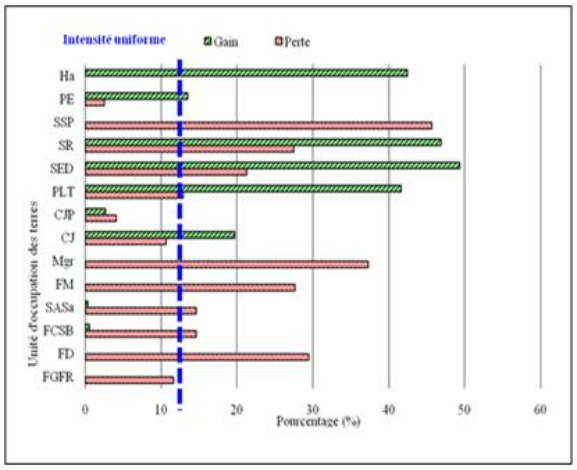

Fig. 11. Land change in intensities and rates by category (2005-2015)

To the left of this line, changes are considered dormant or slow. To its right, changes are classified as active or fast. This being the case, gains in dense dry forests and tree and shrub savannas, crops and fallows under oil palm, and water bodies are slow, while gains in plantations, mosaics of crops and fallows, and dwellings are all fast at 42%, 20%, and 42% respectively. Regarding losses, they are fast in light forests and wooded savannas (15%), dense dry forests (29%), and tree and shrub savannas (15%). Light forests and wooded savannas (15%) experienced slow losses (Fig. 11).

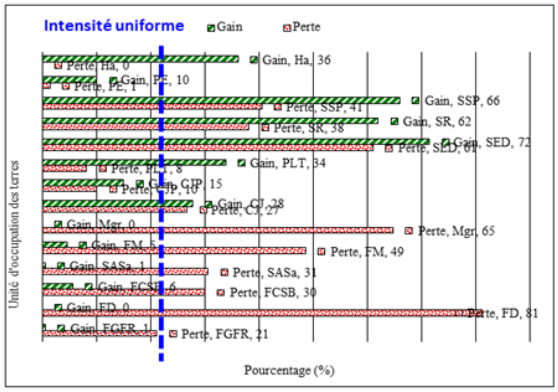

Fig. 12. Land change in intensities and rates by category (2015-2024)

Land cover categories experienced gains and losses relative to the study area's total surface. Gains in dense dry forests and tree and shrub savannas, crops and fallows under oil palm, and water bodies are slow, while gains in plantations, mosaics of crops and fallows, and dwellings are all fast at 34%, 28%, and 36% respectively. Regarding losses, they are fast in light forests and wooded savannas (30%), dense dry forests (81%), and tree and shrub savannas (31%). Crops and fallows under oil palm (10%) and water bodies experienced slow losses (Fig. 12).

DISCUSSION

This study delves into the challenges facing continental aquaculture in southern Benin, aiming to understand its evolution and identify specific hurdles for local aquaculturists. From a socio-economic and demographic perspective, aquaculture in southern Benin is predominantly male-dominated, with men comprising 88.87% and women 10.13%. This gender imbalance points to unequal access to resources, training, or cultural barriers, a trend consistent with other West African aquaculture studies (DSA, 2019; Tiogué *et al.,* 2020; Kusakabe and Thongprasert, 2022). Sociocultural and economic factors often position men as primary farm managers, relegating women to secondary roles.

Exploring strategies to boost female involvement could diversify the sector's stakeholders. Aquaculturists also exhibit diverse educational backgrounds, from illiterate to university graduates (24.19% having higher education). This raises questions about how education influences farm management and the adoption of modern practices, warranting further analysis. Interestingly, 77.10% of aquaculture promoters chose the activity out of passion, while 17.10% did so due to unemployment. While passion drives many, aquaculture also serves as a crucial solution to unemployment, mirroring trends in Africa, Asia, and the Pacific where youth enter aquaculture as an alternative to rural joblessness (FAO, 2018; Fry *et al.,* 2021; Menezes *et al.,* 2024). However, the study suggests that economic motivations for stable income are underestimated compared to the passion aspect.

Regarding aquaculture activities and species, over half of aquaculturists focus solely on aquaculture, though a notable portion integrates it with other sectors like livestock farming or market gardening. This diversification of income sources can enhance resilience to economic and environmental shocks. Oreochromis niloticus (Nile tilapia) and Clarias gariepinus (African catfish) are the dominant species, reflecting local environmental suitability and market demand (Elegbe *et al.*, 2015; Gansa *et al.*, 2018; Edéa *et al.*, 2019). However, cultivating other species such as Spirulina sp., Parachanna obscura, or shrimp remains marginal, a common characteristic in Sahelian regions less favorable to these species (Wuertz *et al.*, 2024).

Aquaculture infrastructure primarily consists of ponds (72.73%), followed by basins (22.46%). These facilities, however, face challenges in water management, predator control, and disease prevention. Developing appropriate infrastructure is vital for sustainable aquaculture. Understanding how aquaculturists adapt their infrastructure to environmental and economic pressures is also crucial.

Major constraints to aquaculture development in southern Benin include financial difficulties (57.89%), predator management (34.49%), and poor sales (19.65%). Other challenges encompass floods, water supply, and the availability of quality feed and fingerlings. Flooding is a persistent issue in swampy areas, potentially linked to human alteration of wetlands, as shown by landscape changes since 2005.

This raises concerns about the sustainability of farms in flood-prone areas. These challenges align with findings from other West African studies, which also identify financial limitations as a primary barrier to aquaculture expansion (ACP Group, 2015; Etienne *et al.*, 2022). Predator management, involving birds, wild fish, or reptiles, is a recurring difficulty in African aquaculture, especially in open or semi-open systems (Otieno, 2019).

The impact of urbanization and land use changes is evident. Land use analysis from 2005 to 2024 reveals significant human impact on swampy areas and natural formations, favoring crops and dwellings.

This transformation directly affects aquatic ecosystems and aquaculture farms, creating new challenges like increased urbanization and flood risks (Secretariat of the Convention on Wetlands, 2021). The expansion of agricultural land and dwellings in wetlands disrupts ecosystems, degrading water quality and increasing pollution (Secretariat of the Convention on Wetlands, 2021). These changes also heighten flood vulnerability for aquaculture farms in coastal and swampy regions (Nwamo *et al.*, 2016; Secretariat of the Convention on Wetlands, 2021). Despite this, concentrating farms in swampy areas near water bodies provides easier water access (Pueppke *et al.*, 2020). Key questions remain: how do land use changes influence aquaculture sustainability, and can land-use planning mitigate these impacts? Finally, forest formations in southern Benin have diminished, reflecting increased anthropogenic pressure from deforestation and agriculture. This necessitates promoting sustainable forest management and environmentally friendly aquaculture. Monitoring urban growth is essential for sustainable development planning. Utilizing transition matrices for future projections can help assess environmental impacts.

CONCLUSION

Aquaculture in southern Benin faces numerous challenges, ranging from economic constraints to environmental problems related to urbanization and land-use changes. However, this activity also presents significant potential for economic development and job creation, provided appropriate solutions are implemented. The information revealed by this study in southern Benin aligns with general trends observed in the West African region. Constraints related to predator management, financial difficulties, and increasing urbanization are widely shared challenges. However, solutions to these problems require an integrated approach that includes technical and financial measures, as well as sustainable management of aquatic ecosystems and surrounding agricultural lands. Possible interventions should include better water resource management, adaptation of infrastructures to environmental risks, and increased support for aquaculturists, particularly through training and improved access to financing. This evaluation represents a crucial step toward guiding public policies for aquaculture development. It will help maximize the social, economic, and environmental benefits this sector offers, at a time when finding sustainable solutions for food security and rural development is increasingly critical. By optimizing the use of natural resources and improving the livelihoods of local communities, aquaculture can become a key lever for a more prosperous and sustainable future in Benin.

ACKNOWLEDGEMENTS

Authors are thankful to the student of the National university of Agriculture for their valuable help in data collections.

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